# Scalable UWB photonic generator based on the combination of doublet pulses

**Vanessa Moreno, Manuel Rius, José Mora, Miguel A. Muriel and José Capmany**

**Abstract:** We propose and experimentally demonstrate a scalable and reconfigurable optical scheme to generate high order UWB pulses. Firstly, various ultra wideband doublets are created through a process of phase-to-intensity conversion by means of a phase modulation and a dispersive media. In a second stage, doublets are combined in an optical processing unit that allows the reconfiguration of UWB high order pulses. Experimental results both in time and frequency domains are presented showing good performance related to the fractional bandwidth and spectral efficiency parameters.

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## 1. Introduction

Ultra-wide band (UWB) transmission technology is very useful in wireless communications, sensor networks, radar, imaging and positioning systems due to its intrinsic benefits that include low power consumption, immunity to multipath fading, interference mitigation, carrier free operation, high data rate and the capability to penetrate obstacles [1]. As known, the Federal Communications Commission (FCC) standard regulates the UWB signals in terms of spectral density and signal power, restricting the coverage area for UWB to a range up to tens of meters [2]. In this context, microwave photonics (MWP) brings two key advantages in UWB systems: by exploiting the low losses of optical fibers it allows the distribution of UWB signals over coverage areas separated from the generation equipment by tens of km, and secondly, it also allows the flexible and reconfigurable generation of different types of UWB signals [3,4].

Different MWP inspired UWB signal generation techniques have been reported in the last years including solutions based on optical spectral shaping and dispersion-induced frequency to-time mapping [5], microwave photonic filtering [6], SOA nonlinear operation [7,8] and phase to intensity modulation (PM-IM) conversion [9,10]. All these proposals even though effective do not represent entirely optimized schemes, since for each Gaussian base pulse generated only one coefficient is inserted to the system and into the generated waveform, hence the need of working with flexible approaches that allow efficient exploitation of the wavelengths involved. Following this principle, designs focused on merging various low order UWB pulses, such as monocycles and doublets provide advantages and are being the subject of current research.

To fully satisfy the FCC requirements complex and sometimes costly structures are required. In this sense, nowadays the approach based on combining various low-order derivatives with inverted polarities to shape pulses into the desired high-order level waveform has been addressed from different perspectives [11–15]. In [11], a photonic generation scheme based on multiple cross-phase modulations and PM-IM conversions in a highly nonlinear fiber (HNLF) is demonstrated. Even though efficient, the presence of multi-wavelength operation and a nonlinear filtering stage increases the cost of the system and it affects its reconfiguration and distance limitation features. In [12], the proposal is to use two optical taps coming from a single electro-optic modulator biased in nonlinear point operation and balanced photodetection. As shown, the critical issue here is the biasing point of the modulator and it is not easily scalable. In [13] a structure based on multiple phase modulations is proposed to accomplish incoherent summation of various monocycle pulses. Moreover, UWB pulses are generated that do not comply with FCC regulations. Also, the use of several phase modulators (PMs) renders a bulky and difficult to integrate approach due to lack of scalability. In addition, previous reports [14] and [15] represent optimized generation techniques proposals, based on potentially low complexity and hence low cost when compared to previous generation schemes. However, they do not achieve a full reconfiguration and scalability features. A recent proposal [16] presents a compact and simple solution, in which a fourth-order UWB signal can be generated with single wavelength operation, but experimental results again are not FCC compliant. Additionally, the spectral efficiencies obtained of the results are far from optimum.

In this work, a novel UWB high-order generator is proposed and experimentally demonstrated providing full scalability and reconfigurability. The operation principle consists on the combination of different doublets generated by means of phase modulation and a dispersive element. We analyze the condition intrinsically related to the dispersive element taken into consideration by means of PM-IM conversion for the generation of a suitable doublet pulse. An optical processor unit (OPU) composed by a set of attenuators and variable delay lines (VDLs) permits to increase the order of the generated pulse. The waveform reconfigurability is achieved from the independent control of the amplitude and time delay for each doublet. Also, the polarity can be changed by means of differential detection. The potential of scalability is related to the number of optical sources that is lower than in previous reports based on microwave photonic filters [6]. For instance, two laser sources were employed for the generation of an UWB triplet pulse with a high spectral efficiency of 60% and fully compliant with the FCC spectral mask regulations.

## 2. Principle of operation

In general, the derivatives of Gaussian pulses are employed for UWB pulse generation [13]. Although monocycle and doublet pulses are used due to their simplicity, high-order derivatives of Gaussian pulses are more suitable candidates for UWB systems in terms of spectral efficiency [14]. For instance, triplet and quadruplet pulses allow to increase spectral efficiencies from 20 up to 60%, respectively. In order to reduce the system complexity when UWB high order pulses are required, our work is focused on the possibility of increasing a derivative order from the combination of different UWB lower-order pulses with inverted polarities. Figure 1 depicts our scalable proposal to generate high order UWB pulses.

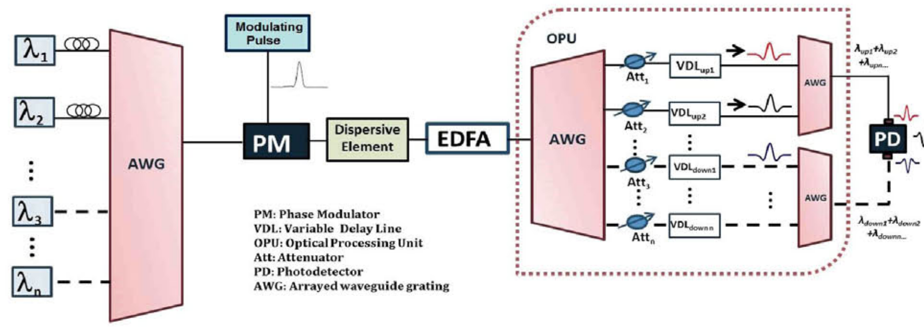


Fig. 1. Full scalable scheme for generating high-order UWB pulses.

In the first segment of the proposed scheme, light from a set of N optical sources is launched to a phase modulator (PM) by means an array waveguide grating (AWG). The PM is modulated by Gaussian pulses coming from an electrical pulse generator providing an OOK data sequence to be transmitted. Then, the phase-modulated optical signal is applied to a dispersive element that provides the required phase-to-intensity conversion. Indeed, the combination of PM and dispersive element provides a doublet pulse by means of its equivalent microwave photonic bandpass filter, for each single-wavelength laser [9].

After the phase-to-intensity conversion process, the set of optical taps are launched into the optical processor unit (OPU) to reconfigure the high order pulses. At the OPU, each UWB doublet pulse coming from one single-wavelength source is treated independently and is distinguishable from other doublets by means of their corresponding optical wavelength using a second AWG. The OPU allows to customize the amplitude and delay parameters for each doublet separately. Therefore, by means of a demultiplexing structure combined with a set of attenuators and variable delay lines (VDLs), the signal outputs are multiplexed into two branches that feed a balanced detector that determines the positive or negative polarity of the taps. Note that an Erbium Doped Fiber Amplifier (EDFA) is placed before OPU to compensate optical losses.

The use of the balanced photodetector has a significant importance in the process, beyond being a simple optical-electrical convertor since, to gain a derivative order, the low order pulses to be reconfigured and summed up need to be previously inverted in polarity.

In this way, our proposal consists on an equivalent N-tap microwave photonic filter with positive and negative coefficients with reconfigurable amplitude and optical delays at the OPU. Each optical tap is obtained by the combination of phase modulation and a dispersive element. In this way the scalability of the system depends on the availability of multiple WDM channels. In our case, the number of optical sources is reduced as compared to those schemes that implement each optical tap with an independent Gaussian pulse [6, 8].

Selection of a suitable dispersive element is not a trivial issue since the quality of the spectrum corresponding to the UWB doublet generated determines directly the high-order pulse to be produced. For instance, Fig. 2 depicts simulated UWB doublets and their corresponding theoretical spectra for a simple characterization employing various SMF links as a dispersive element. The dispersion into consideration ranged between 170 ps/nm (10 km SMF fiber link) and 425 ps/nm (25 km SMF fiber link). Apart from the bandpass filtering effect of the phase-to-intensity conversion as [9] predicts, we show that a notch filter is achieved at a frequency that depends on the amount of dispersion for a given Gaussian pulse driving the PM. It is noticeable the better fit of the system employing a dispersion close to 340 ps/nm (20 km SMF fiber link) in terms of the FCC regulation . In this case, the notch is centered at the GPS band which limits the UWB generation performance at low frequencies.

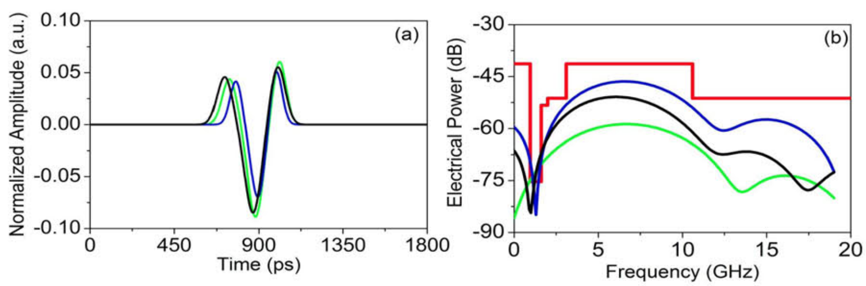


Fig. 2. (a) Simulated doublets with various lengths dispersive elements and (b) their respective theoretical spectral representations. Green lines correspond to a dispersion equivalent to 10 km SMF link, blue lines correspond to 20 km and black lines correspond to 25 km. FCC mask is plotted in red line.

## 3. Experimental results

In order to verify and validate the performance of the proposed configuration, we first determine the dispersion initially required as discussed in Fig. 2. After analyzing the theoretical results in section 2, we find that the most suitable scenario when comparing with the FCC mask is an accumulated dispersion around 340 ps/nm. In our experimental implementation, we consider a 20 km SMF fiber length as a dispersive element taking into account that the SMF-28 fiber has a chromatic dispersion of approximately 17 ps/nm.km at the operating window (1550 nm). Firstly, we analyze the generated pulse when a laser centered at 1550.12 nm is used to implement an optical tap propagating through the dispersive element. The PM is modulated by a Gaussian pulse with a fixed pattern of one "1" and sixty-three "0" (total 64 bits) and 12.5 Gb/s bit rate. The PM has an insertion loss of 3.5 dB and a 3dB bandwidth of 20 GHz. Figure 3 shows both the frequency and time domain representations for the corresponding doublet generated with those parameters. Figure 3(a) plots the experimental results for the doublet pulse with a full-width at half-maximum (FWHM) about 45 ps. The blue line corresponds with theoretical prediction. On the other hand, Fig. 3(b) represents the corresponding experimental RF spectrum (black line) compared to the FCC mask (red line). The blue line represents the theoretical results corresponding to the doublet pulse of Fig. 3(a). First of all, it is remarkable that the doublet pulse has a notch around GPS band that fully complies with the FCC spectral mask regulation. The generated doublet achieves a fractional bandwidth of about 133% and a spectral efficiency of about 23%.

For the purposes of fractional bandwidth and spectral efficiency calculations, we have taken into consideration the theoretical approaches presented in [14] and [17]. The mask-filling efficiency of a particular signal is defined as the ratio between the average power of the pulse within the useful UWB band and the total admissible power under the FCC mask within the same band which must be maximized. On the other hand, based on the 2002 FCC definition, any signal having −10 dB fractional bandwidth larger than 20% is considered as UWB.

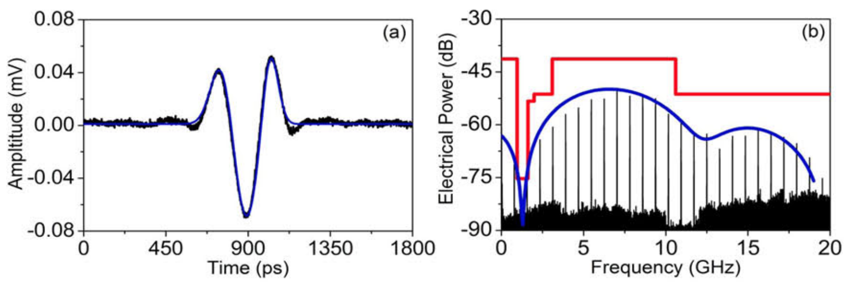


Fig. 3. (a) Time domain representation of obtained doublet with a 20km SMF length and (b) corresponds to spectral representation. Black lines represent experimental results and blue lines corresponds to theoretical prediction. In addition, FCC mask is plotted in red line.

Once the dispersion parameter has been optimized in our case, we exploit the scalability of the system to improve the spectral efficiency of the generated pulses. The main objective in this experimental setup is to determine the proper matching between the generated spectrum and the specifications settled by the FCC.

In this sense, a FCC mask compliant UWB triplet is generated. The operation principle of the design relies on the combination of two second-order derivatives of Gaussian pulses separated in time around 130 ps and generated by means of two laser sources, labeled as $\lambda_1$ and $\lambda_2$. Optical sources $\lambda_1$ and $\lambda_2$ are centered at 1550.12 nm and 1550.92 nm, respectively, with an optical power of 10.50 dBm. The data to be transmitted in the scheme is fed to the PM with a bit sequence pattern of 64 bits (100…0) at a repetition rate of 12.5 GHz. As it was established in Fig. 1, the base low-order doublets are accomplished through PM-IM conversion and the generated signals are introduced into the reconfiguration stage (OPU) by means of an AWG. In this sense, each doublet is customized in terms of amplitude and delay through a set of attenuators and variable delay lines (VDLs), in order to optimize the output signal. In this case, a VDL introduces a delay of 142 ps between both optical taps in order to compensate the chromatic dispersion introduced by the fiber link (272 ps) due to their wavelength separation.

Finally, because of the differential detection provided by the balanced photodetector, the pulse introduced through the upper arm is combined with its inverted version produced in the lower arm, leading to the expected higher order UWB waveform.

Figure 4(a) exhibits the obtained UWB triplet waveform, where the blue line corresponds to the theoretical prediction and Fig. 4(b) plots its corresponding spectral representation. This UWB triplet depicts a fractional bandwidth of 116% along with a spectral efficiency with a value as high as 60%. As expected, a perceptible increase of the spectral efficiency occurs when comparing the previously obtained doublet in Fig. 3, which shows a spectral efficiency around 23%. Therefore, it is possible to obtain an UWB triplet compatible with FCC standard purposes by using two single-wavelength lasers and a PM, which do not require any control as previous reports [12].

Finally, it is interesting to remark the potentiality of the system to be integrated on a single chip by means of the available technology [18].Specifically, the building blocks which can be implemented with current technology are the PM-IM conversor [19] and the OPU including the differential detection stage [20, 21]. Indeed, reference [19] proposes an approach for a PM-IM convertor with performance improvement of phase-modulated microwave links based on ring resonators. On the other hand, for the implementation of delay lines located at the OPU, a compact approach based on dispersive photonic crystal waveguide is reported in [20]. Moreover, a novel and interesting solution is proposed by [21] involving the conceptualization of an AWG made of Si-rich silica (SiOx) waveguides.

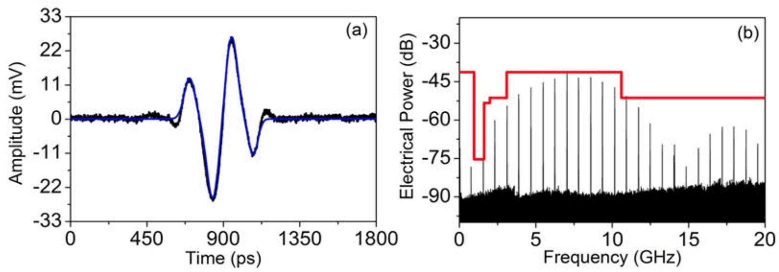


Fig. 4. (a) Generated UWB triplet with its time domain representation and (b) corresponding spectrum. FCC mask is plotted in red line.

## 4. Conclusions

We have proposed an efficient, reconfigurable and scalable UWB generation system based on a two stage configuration composed of a phase to intensity conversion part and an optical processing unit OPU. Each lower-order doublet is obtained by PM-IM conversion by means of a Gaussian pulsed modulated phase modulator and a dispersive device. These optical taps can be generated at multiples wavelengths and each one is treated as a different sample in the OPU that operates as a wavelength selective transversal filter. The characteristics of the output UWB signal are reconfigurable by changing the amplitude and delays of each sample. We have experimentally proved the feasibility of the concept by using two optical sources to implement a UWB triplet signal satisfying the FCC requirements. The key element of the first section is implemented by means of a 20-km long SMF fiber link operating as a dispersive media to perform the phase to intensity conversion when an input phase modulated signal is injected. The OPU allows a full reconfigurability in terms of amplitude and optical delay for each optical tap. When comparing the doublet employed as the seed lower order pulse and the generated UWB triplet, we obtain an improvement in terms of spectral efficiency from 23% to 60% as expected. When compared to theoretical values, an excellent agreement between theory and experimental results can be appreciated.


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